

Thermal effects on the Fission Barrier of neutron-rich nuclei

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Abstract. We discuss the fission barrier height of neutron-rich nuclei in a r-process site at highly excited state, which is resulted from the beta-decay or the neutron-capture processes. We particularly investigate the sensitivity of the fission barrier height to the temperature, including the effect of pairing phase transition from superfluid to normal fluid phases. To this end, we use the finite-temperature Skyrme-Hartree-Fock-Bogolubov method with a zero-range pairing interaction. We also discuss the temperature dependence of the fission decay rate.

Keywords: Fission, neutron-rich nuclei, temperature, r-process, Hartree Fock Bogoliubov

PACS: 24.75.+i, 21.00.00, 21.60.Jz

INTRODUCTION

R-process is considered to be a leading candidate responsible for the synthesis of elements heavier than $A \sim 70$ [1]. Since the study of r-process involves many kinds of nuclei which extend to the neutron-rich region, one often has to predict theoretically their masses and beta-decay rates. Although the recent experimental exploration to nuclei close to neutron- (proton-) drip line will make the study of r-process more reliable, a part of heavy neutron-rich nuclei produced by r-process are still difficult to examine experimentally. Notice that those heavy nuclei have a characteristic decay channel, that is fission. R-process with fission of heavy neutron-rich nuclei has been discussed and considered to explain the formation of elements with $A \sim 130$ [2].

One of the important quantities which govern the fission process is a fission barrier. So far, the theoretical study of fission barrier height has been limited to the zero-temperature [3, 4, 5]. This is justified if the excitation energy is not so high and the corresponding temperature is much lower than the critical temperature T_{crit} , at which pairing correlations vanish (the critical temperature may be approximated with $T_{crit} \simeq 0.5\Delta_{T=0}$ [6]). The pairing gap parameter for heavy nuclei is relatively small. In addition, heavy neutron-rich nuclei involved in the r-process may have a high excitation energy, leading to the pairing phase transition, as a consequence of the beta-decay or the neutron-capture. The highly excited state may decay via fission. The neutron-induced fission has a significant role in the environment of high neutron density, while the beta-delayed fission is important when the neutron density is lower than about 10^{22}cm^{-3} [7]. If the pairing phase transition occurs, the fission probability will be considerably affected.

The aim of this work is to assess the sensitivity of fission barrier height and fission probability of hot neutron-rich nuclei to the temperature. We study ^{236}U , which is close to the stability line, as well as ^{286}Fm , which is neutron-rich nucleus relevant to the r-process.

FRAMEWORK

In this work, we use the finite temperature Skyrme-Hartree-Fock-Bogoliubov (FTHFB) method [6, 8] with a zero-range pairing force. The framework is the same as the zero-temperature HFB except for the particle density and pairing tensor. They are modified according to the Fermi-Dirac distribution of quasi-particle occupancy. The thermal averaged particle density and pairing field are given as,

$$\rho_T(\vec{r}) = \sum_i \left(V_i^*(\vec{r}) V_i(\vec{r}) (1 - f_i) + U_i^*(\vec{r}) U_i(\vec{r}) f_i \right), \quad (1)$$

$$\Delta_T(\vec{r}) = \frac{1}{2} V_q \sum_i U_i^*(\vec{r}) V_i(\vec{r}) (1 - 2f_i), \quad (2)$$

where f_i is the quasi-particle occupation probability defined by $f_i = 1/(1 + e^{\beta E_i})$, β being $\beta = 1/kT$. We have assumed the volume-type pairing interaction, $V_{pair}(\vec{r} - \vec{r}') = V_q \delta(\vec{r} - \vec{r}')$, where $q = p$ corresponds to proton and $q = n$ neutron. U_i and V_i are the quasi-particle wave functions, which are the solution of the FTHFB equation given by,

$$\begin{pmatrix} h_T - \lambda & \Delta_T \\ \Delta_T & -h_T + \lambda \end{pmatrix} \begin{pmatrix} U_i \\ V_i \end{pmatrix} = E_i \begin{pmatrix} U_i \\ V_i \end{pmatrix}, \quad (3)$$

where h_T and Δ_T are the thermal averaged mean field Hamiltonian and pairing field, respectively, and E_i is the quasi-particle energy.

In this work, we use the quadrupole operator \hat{Q}_2 as a constraining operator. For simplicity, we assume the reflection and axially symmetric nuclear shapes. Deformation parameter used here is defined by $\beta = \sqrt{5/15\pi} (4\pi/3AR_0^2) \langle \hat{Q}_2 \rangle$, where R_0 is the nuclear radius parameter given by $R_0 = 1.1A^{1/3}$ (fm).

RESULTS

Figure 1 shows the total energy $E = \langle H \rangle$ at temperatures from $T = 0.0$ to 0.8 MeV. We use SLy4 for the Skyrme parameter set and $V_p = -295.369$, $V_n = -286.339$ MeV for the pairing strength, which are determined so as to reproduce the ground state energy of ^{236}U . We determine the fission barrier height from the difference between the highest and the lowest energy in the potential energy surface. Fig. 1 indicates that the barrier height of ^{236}U continuously increases with temperature, while that of ^{286}Fm first increases but begins to decrease at $T=0.6$ MeV. This feature is due to the difference in the behavior of the pairing energy between the two nuclei at the maximum and minimum points, where the energy is the highest and lowest, respectively. The pairing energy at the minimum and maximum points as a function of temperature is shown in Figure 2. The pairing energy at the minimum point is larger than that at the maximum point for ^{236}U , while it is opposite for ^{286}Fm . Moreover, the pairing energy at the minimum for ^{286}Fm has much weaker temperature dependence than that at the maximum point. All of these features lead to the behaviors shown in Figure 1.

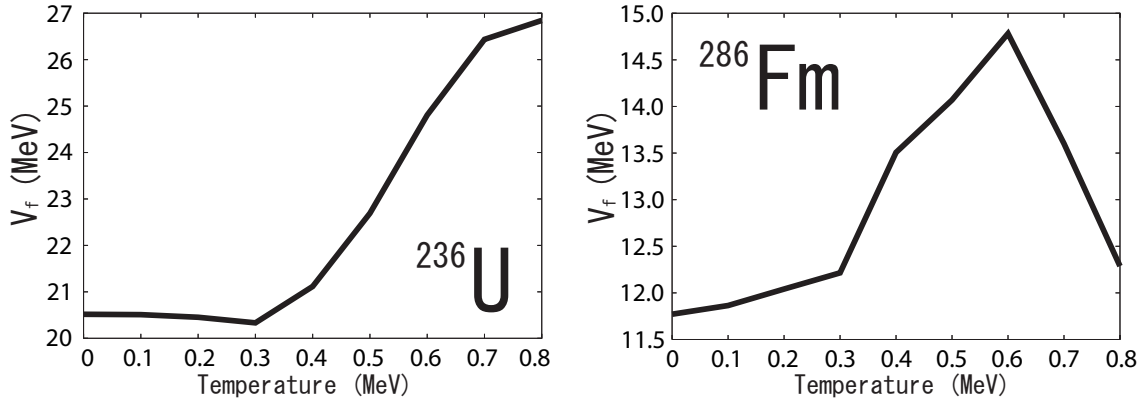


FIGURE 1. Fission barrier height as a function of temperature for ^{236}U and neutron-rich nuclei ^{286}Fm .

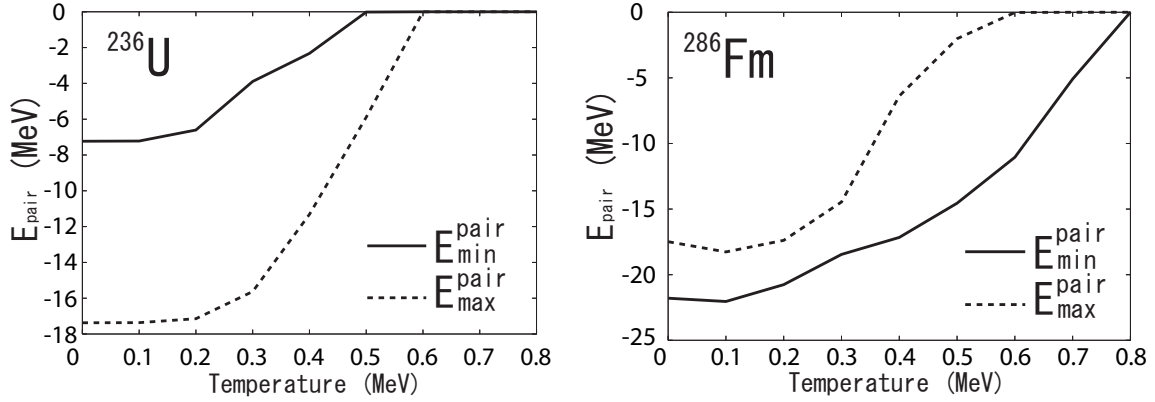


FIGURE 2. Pairing energy at the minimum and maximum points for nuclei ^{236}U and ^{286}Fm .

In order to estimate the decay rate of these nuclei, we adopt the Bohr-Wheeler formula given by,

$$\Gamma_f = \frac{\omega_0}{2\pi} e^{-\beta V_f}. \quad (4)$$

The quantity ω_0 is the curvature at the minimum point,

$$\omega_0 = \sqrt{\frac{V''(\beta_{g.s.})}{m}}, \quad (5)$$

where m is the mass parameter. We use the liquid-drop-model for m given by $m = (3/4\pi)(1/0.04)Am_nR_0^2$ [9], where m_n is the nucleon mass. We show the results in Figure 3 as a function of the excitation energy, where we use the formula $E^* = (A/8)T^2$. The solid line is obtained with the fission barrier at zero-temperature (the cold model) while the dashed line takes into account the temperature dependence of the fission barrier (the hot model). By using the temperature dependent fission barrier height, the decay widths

decrease by about 10^{-1} for ^{286}Fm , and 10^{-3} for ^{236}U at excitation energies larger than 5 MeV. We can see that the results of the cold and hot models for ^{286}Fm become close to each other at higher temperatures due to the temperature dependence of fission barrier as seen in Figure 1.

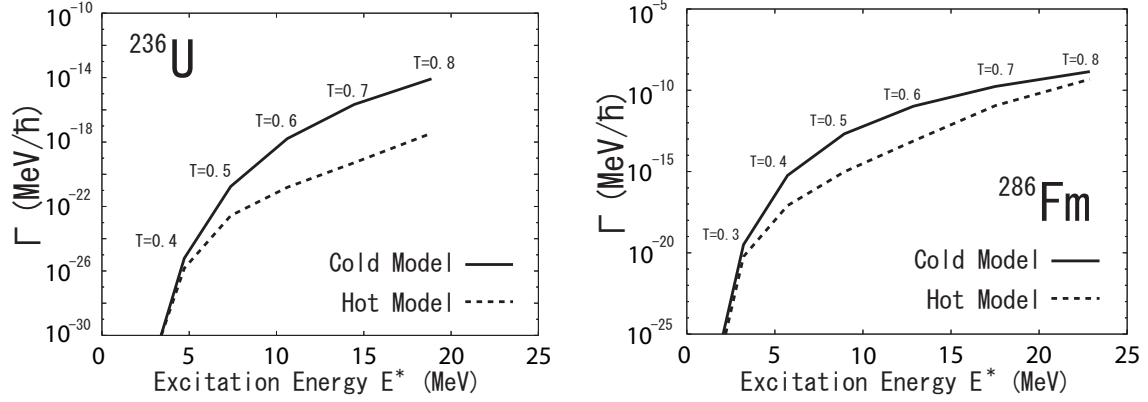


FIGURE 3. Decay width Γ_f for nuclei ^{236}U and ^{286}Fm . The cold model uses the fission barrier at zero-temperature, while the hot model takes into account the temperature dependence of fission barrier.

In summary, we have calculated the temperature dependence of the fission barrier for neutron-rich nucleus ^{286}Fm and the ^{236}U nucleus near the stability line. For this purpose, we used the finite-temperature Hartree-Fock-Bogoliubov with a zero-range pairing interaction. We found that the fission barrier height of ^{236}U becomes large at a high temperature and that that of ^{286}Fm shows a decrease at $T=0.6$ MeV because of the temperature dependence of the pairing energy. We used the Bohr-Wheeler formula in order to calculate the fission rate. By taking into account the temperature dependence of fission barrier, the decay widths is suppressed by a factor of 10^{-1} to 10^{-3} .

This work was supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology by Grant-in-Aid for Scientific Research under the program number 19740115.

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